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A VOLCANOMAGNETIC OBSERVATION ON MOUNT ST. HELENS, WASHINGTON

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Abstract. Total magnetic fields were recorded at five sites on Mt. St. Helens between 23 October and 11 November 1981, an interval which included an extrusive dome-building eruption of the volcano. Two of the magnetometers located in the volcano's crater measured reversible magnetic changes, which correspond to fluctuations in tilt measured nearby. However, the relationship is highly nonlinear. Electric fields were measured on the east flank of the volcano near its summit to search for electrokinetic effects. They show no correlation with the magnetic changes and, in the long term, are uncorrelated with eruptive activity. Our favored interpretation of the magnetic changes is that they result from stress-induced changes in the magnetization of the volcano. Magnetic field values returned to pre-anomaly values. This reversibility rules out pressure-induced magnetization as the dominant mechanism and places an upper limit of σ ~300 bars on the stress changes. The limited spatial extent of the magnetic anomaly field places the source of stress at shallow depth beneath the crater floor consistent with models based on strain data.

Introduction

The piezomagnetic sensitivity of magnetic minerals in rocks provides a physical mechanism by which the local geomagnetic field is expected to change due to stressing of the earth's crust (Wilson, 1922; Kalashnikov, 1954). Magnetic changes have been measured on several active volcanoes (Rikitake, 1951; Yukutake and Yabu, 1962; Johnston and Stacey, 1969a, Johnston and Stacey, 1969b, Davis et al., 1973, Davis et al., 1979, Pozzi et al., 1979). They have the characteristics of transient, localized perturbations of the geomagnetic field during volcanic activity, with time constants of hours to weeks. None have been observed by more than one instrument, so that their spatial extent is in question, and in only one case (Davis et al., 1979) were simultaneous strain and magnetic measurements made. If volcanic deformation is elastic, proportionality of stress and strain requires that piezomagnetic changes should correlate with strains. We report here measurements of magnetic fields on an array of five recording proton magnetometers on Mt. St. Helens with simultaneous measurements of tilt and electric fields, taken during a dome-building eruption on the volcano.

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The piezomagnetic stress sensitivity of crustal rock is theoretically explained as arising from stress-induced changes in the magnetocrystalline energy of magnetic grains. The changes cause rotation of the spontaneous magnetization and movement of domain walls (Kapitsa, 1955; Kern, 1961; Stacey, 1962; Nagata, 1970; Stacey and Johnston, 1972). Moderate stressing of (σ<300 bars = 30 M Pa) rocks, for which the soft component of the magnetization is small, generates reversible magnetization changes, i.e., they recover when the stress is removed. Irreversible changes have been shown to occur both in rocks subjected to large stresses (Carmichael, 1968; Martin et al., 1978) and also at low stress, but in rocks containing a large component of soft magnetization (Nagata and Carleton, 1968, 1969a, 1969b). The latter effect has been termed pressure-induced magnetization or PRM (Nagata and Carleton, 1968) and, in some samples, can be as much as an order of magnitude greater than the reversible effect. However, the results presented here and those of previous investigations show that volcanomagnetic effects are reversible, (i.e., the magnetic field changes return to the base-line after eruptive activity) favoring low stress (<300 bars) piezomagnetic effects as the dominant mechanism.

Models of volcanomagnetic effects (Stacey et al., 1965; Davis, 1976; Sasai, 1979) predict that localized geomagnetic changes of several nanoteslas should occur about an erupting volcano due to piezomagnetic changes in the volcano's magnetization. Strains of order 100 μ radians, if perfectly elastic, would generate a fractional change in magnetization of 6×10^{-3} (assuming a stress sensitivity of 2×10^{-4} bar^{-1} and rigidity modulus of 3×10^{5} bars for volcanic basalt). Corresponding magnetic field changes amounting to ~12nT are expected to occur above magnetic rock on a volcano (magnetization 5×10^{-3} emu or 5 A m^{-1}) strained to this extent, with the effect directly proportional to the intensity of the magnetization. Other mechanisms which might change the magnetic field include heating or cooling of the magnetic rock and electric current flow generated by the electrokinetic effect (Fitterman, 1978, 1979). Because the thermal conductivity of rock is so low, the former mechanism is thought to have a time constant much longer than the time constants of the magnetic transients that have been observed.

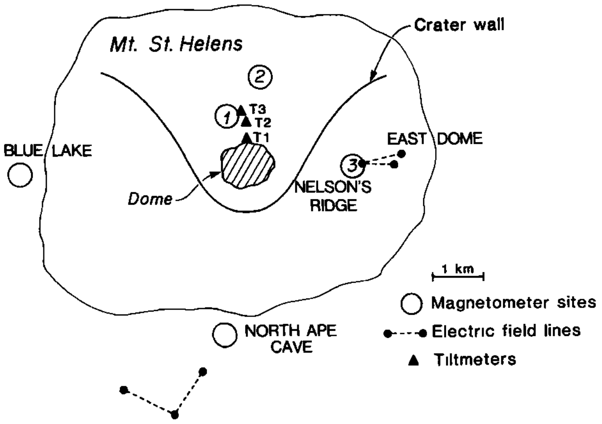

Fig. 1. Location map.

The latter mechanism results from the electric currents generated by fluid motion through geologic materials. The motion causes charge separation and electric fields capable of driving electric currents. Simultaneous measurement of magnetic and electric field can be used to discriminate whether magnetic changes are of electrokinetic or piezomagnetic origin, since piezomagnetic changes will not be accompanied by electric field changes, whereas electrokinetic ones will (Fitterman, 1979). Electric fields were measured on Mt. St. Helens for this purpose.

The Experiment

Previous magnetic measurements (Johnston et al., 1981) on Mt. St. Helens revealed that at the time of the catastrophic May 18, 1980 eruption, the field at Blue Lake (BL), a site five kilometers west of the crater (Figure 1), increased by 9 ± 2 nT. Following this, large transients are seen in the record during the subsequent smaller eruptions of 1980. The explanation for the 9 nT increase was regional elastic stress release; redistribution of magnetic material resulting from removal of a volume of 2.5 km^3 from the volcano's summit would have given changes of the opposite sign (Johnston et al., 1981). Unfortunately, of the three magnetometers installed (10 days) before the eruption, only one survived. Normally, at least two are required so that differences can be taken to cancel out externally generated magnetic activity, revealing changes that originate locally. Therefore, it has been difficult to distinquish disturbances originating within the volcano from those due to inonospheric currents induced either by eruptive shock waves or solar activity.

A second magnetometer was installed at North Ape Cave (NAC) in August 1980 (Figure 1). In addition, during September 1980 we installed two recording electric field lines on the east flank of the volcano (Figure 1), extending 0.6 km and 1.5 km radially from the summit between Nelson's Ridge and East Dome. We recorded voltage differences between end point electrodes which are comprised of two-meter long copper rods inserted in post holes filled with a mixture of salt and volcanic ash. In approximately one and one-half years of record no electric field changes have been observed which correlate with magnetic changes, eruptions or dome extrusions. The variation in this measurement of 0.1 volts places an upper limit on the electrokinetic effects generated by the eruptive activity.

In October 1981, two recording magnetometers were installed in the crater within one kilometer of the dome (Stations 1 and 2 of Figure 1) and a third magnetometer at Nelson's Ridge (Station 3). All magnetometers are of the proton precession type, with sites 1-3 taking readings once a minute and sites Blue Lake and North Ape Cave taking readings once every ten minutes. Biaxial tilts were recorded in the crater at sites T1, T2, and T3 (Figure 1).

Immediately after the initiation of recording (October 23, 1981), the magnetic difference field, Station 1 - Station 2 (STA1 - STA2), began to increase at the rate of 1 nT/day until October 27, when the trend reversed. The accumulated 4 nT then relaxed over a period of 16 hours (Figure 2). Comparison with the azimuthal tilt T1 (Figure 2) shows that this excursion corresponds to a fluctuation in that record. The near-summit electric field (Figure 2), measured on the 1.5 km line between East Dome and Nelson's Ridge, is not similarly affected. On October 30, 1981, seven days after installation, an extrusive dome-building eruption took place at the lava dome, a composite structure built by successive extrusions and intrusions. Figure 3 shows the magnetic differences every ten minutes for NAC-BL, STA3-BL, STA2-BL, and STA1-BL along with the radial tilt record at T_1. Equipment problems at STA3 and telemetry loss at NAC account for data gaps in those records. The tilt record (Figure 3) shows that major radial tilting of the crater floor began on October 26 and reached a maximum on October 30. We used Blue Lake as a reference station for the magnetic differences because it is the most distant and because, as far as we can judge, the volcanomagnetic anomaly is confined near the crater magnetometers. With this assumption, the results show that STA2 recorded the maximum change of 5 nT which, after the initial decrease prior to the 27th, increased to a maximum coincident with the beginning of extrusion and then relaxed by about 1.2 nT over the following 12 days. The initial behavior of STA1, closer to the dome, differs markedly from that of STA2. A steady increase is seen reaching a maximum of 1.5 nT at the time of the event, followed by a relaxation of the increase over the following ten days. The fields measured at STA3 and NAC are both noisy and discontinuous, but they contain no evidence that the anomaly field extends to them. Much of the noise is due to imperfect cancellation of the diurnal variation. However it reduces significantly on taking daily averages (dotted curves on Figure 3).

Mathematical modeling of the radial inflation tilts measured at T_1 (120μ), T_2 (74μ), and T_3 (74μ) using the Mogi model (i.e., a center of dialation located beneath the dome, Mogi, 1958) gives an estimate of the maximum source depth of the stressing of about 1 km. The Mogi model corresponds to a point source of pressure in an elastic half-space. We use it here as a first order approximation to the stress source which, if more surface deformation data were available, might warrant inclusion of higher order terms. The misfit to the radial tilts at T_1, T_2, and T_3 is 5, −15, 13 μ radians, respectively. However such a simple model predicts zero azimuthal variation in conflict with the record in Figure 2. We therefore regard the model as a guide only to the depth of the stress center consistent with the sparsity of deformation data available. The volcanomagnetic anomaly for such a shallow source is expected to be confined to the summit region of the volcano as is observed.

Throughout the period, the electric field record (Figure 2) remains essentially flat and uncorrelated with the magnetic changes seen in the crater. These measurements made outside the magnetic anomaly field are insufficient to rule out electrokinetic effects as its source. However, in view of the generally observed lack of correlation between electric fields, tilting, and magnetic changes for this and a number of other such episodes of eruptive activity, as well as explosive eruptions in October 1980, we attribute the magnetic changes to piezomagnetic rather than to electrokinetic phenomena. Both their magnitude and spatial distribution qualitatively agree with computed piezomagnetic anomalies. Quantitative comparison will require 1) estimates of the magnetization distribution within the volcano from surface geomagnetic field measurements, along with 2) direct measurements of the stress sensitivity of the volcanic rock, and 3) inversion of the surface strain data to estimate the stress field. Stacey and Banerjee, 1974, list the critical stresses necessary to irreversibly rotate domains from one easy direction to another. The values are

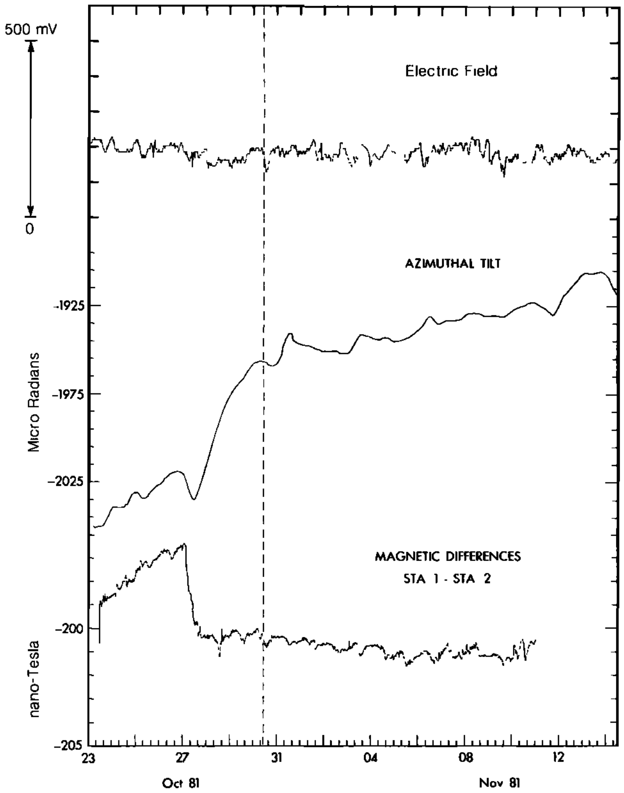

Fig. 2. Electric, magnetic and tilt fields.

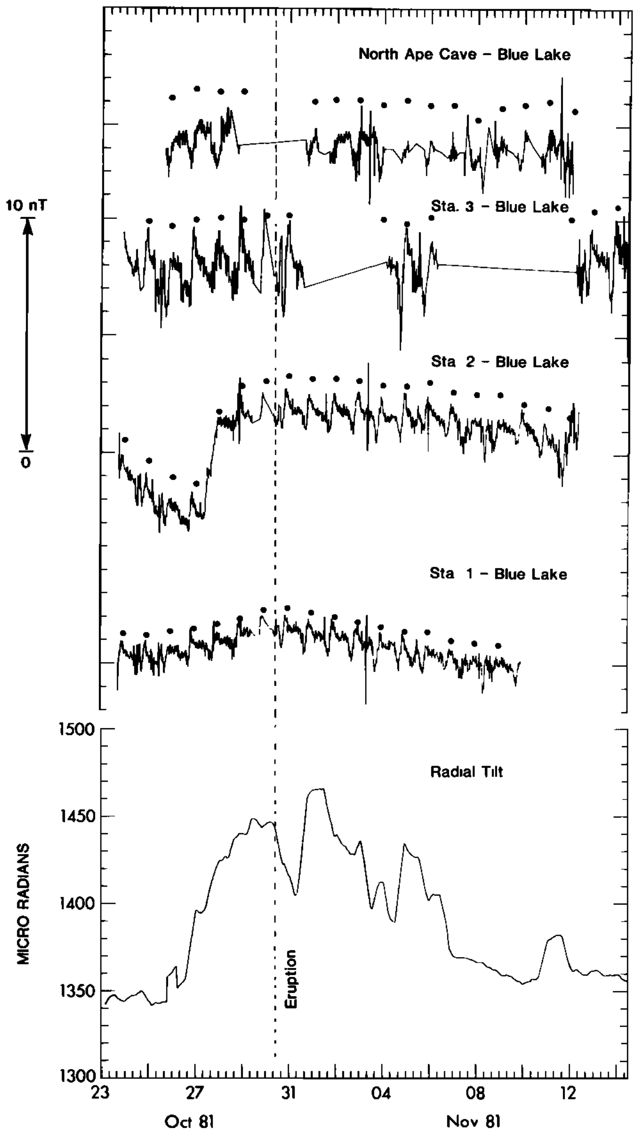

Fig. 3. Magnetic differences and radial tilt.

typically about 300 bar. If such irreversible changes were to occur, the volcanomagnetic anomaly field would exhibit a permanent offset. However, the observed magnetic changes of Figure 3 return to the base-line, placing an upper limit of σ ~300 bars on the stress variation. This reversibility also rules out PRM as a dominant mechanism. The nonlinear relationship between magnetic field changes and tilt (Figures 2 and 3) could be due to anelastic deformation of the volcano such as block rotations or brittle failure. The magnetic variations would then discriminate elastic from anelastic strains since stress change associated with the former gives rise to magnetic variation which is absent from the latter.

Conclusions

We have shown that tilt-related magnetic transients occurred on Mt. St. Helens volcano within 1 km of the dome during an extrusive episode. In contrast to the major eruption of

May 18, 1980, this event released orders of magnitude less elastic energy. Were stresses to rise to those levels again, a regionally more extensive anomaly field is expected. The observations at Blue Lake at the time of that eruption (Johnston et al., 1981) may have been due to such an anomaly field. We are continuing these observations to examine further events over as wide a range of eruptive activity as possible.

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